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Earth's Future

Supporting Information for

Towards a comprehensive climate impacts assessment of solar geoengineering

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Contents of this file

Supplemental Section 1: The climate response to sunshade geoengineering
Supplemental Section 2: Differences between sunshade geoengineering and other types of solar geoengineering
Supplemental Section 3: Solar geoengineering and the five reasons for concern
Supplemental Section 4: Methodology for Supplemental Figure 1
Supplemental Section 5: References
Supplemental Section 6: Supplementary figures

Supplemental Section 1. The climate response to sunshade geoengineering

Greenhouse Gas (GHG) forcing and the forcing arising from any form of solar geoengineering act differently in the shortwave and longwave components of the Earth's energy budget and have different spatial and seasonal distributions [Kravitz *et al.*, 2013]. As discussed in more depth below, simulations consistently show that sunshade geoengineering produces a greater change in global mean precipitation than does an equivalent change in temperature from GHG concentration changes (Supplemental Figure 1 a and b) [Tilmes *et al.*, 2013]. Solar geoengineering will have little effect on some of the consequences of GHG emissions (Supplemental Figure 1c), such as the direct effects of CO₂ on the chemistry and acidity of the oceans [Matthews and Caldeira, 2007]. Solar geoengineering would also likely create novel risks that will depend largely on the magnitude of its deployment (Supplemental Figure 1d), such as the reduction in stratospheric ozone seen in simulations of stratospheric sulphate aerosol injection [Pitari *et al.*, 2014; Tilmes *et al.*, 2009].

If solar geoengineering deployment that were exerting a strong cooling effect were to cease abruptly, an initially extremely rapid warming would follow at a rate of up to several times the decadal rate of global warming that would have occurred had solar geoengineering not been deployed [Jones *et al.*, 2013; Matthews and Caldeira, 2007; Wigley, 2006]. However, it is important to stress that such a “termination effect” is far from inevitable. If CO₂ is drawn down from the atmosphere in significant net amounts over the coming centuries, solar geoengineering could gradually be phased out without a change in temperatures. Furthermore, solar geoengineering need not be deployed to offset all greenhouse warming indefinitely (as is typically simulated); instead it could be deployed in a moderate, temporary manner to slow warming [MacMartin *et al.*, 2014], or an initially large-scale deployment could be phased out over the course of decades [Irvine *et al.*, 2012].

Due to the balancing of the opposing effects of GHG and solar forcings on the shortwave and longwave components of the energy budget, simulations deploying sunshade geoengineering to fully offset the effects of elevated GHG concentrations on global annual mean temperature show a small net cooling in tropical regions (especially oceanic regions) and a small net warming at high latitudes (e.g. Supplemental Figure 2a) [Kravitz *et al.*, 2013; MacMartin *et al.*, 2015; Schmidt *et al.*, 2012]. Such a deployment would also be somewhat more effective at offsetting changes in summer temperatures and extreme high-temperatures than winter temperatures and extreme low-temperatures, and would produce small reductions in the diurnal temperature range that would be largest in arid regions [Curry *et al.*, 2014; Lunt *et al.*, 2008]. Projections of changes in temperature extremes are uncertain. However, because sunshade geoengineering reduces average temperature changes, feedback processes are reduced, inducing a smaller spread in model projections (Supplemental Figure 2a) [Irvine *et al.*, 2014a; MacMartin *et al.*, 2015].

The different effects of solar and GHG forcings are more pronounced in the case of the hydrological response than for the temperature response. In simulations where CO₂ concentrations are quadrupled from a pre-industrial baseline and sunshade

geoengineering is deployed to fully offset the temperature change, global mean precipitation was found to be reduced by 4.5% below the pre-industrial level, compared with an increase of 6.9% above pre-industrial in the high-CO₂ scenario [Tilmes *et al.*, 2013]. Analogously, if the objective were to offset global mean precipitation change due to elevated GHG concentrations using sunshade geoengineering, then the global mean temperature increase would only be partially compensated, i.e., it would still be higher than in the pre-industrial era (Supplemental Figure 1 a and b) [Tilmes *et al.*, 2013]. Thus, sunshade geoengineering cannot simultaneously restore global mean precipitation *and* global mean temperature to pre-industrial conditions, meaning there would still be some degree of climate change, and hence climate impacts, regardless of the manner in which sunshade geoengineering were to be deployed. At the regional scale, simulations of a full deployment of sunshade geoengineering show substantial changes in the pattern of precipitation, creating conditions that are markedly different from both a relatively low-GHG state and a high-GHG state without sunshade geoengineering (Supplemental Figure 2b) [Kravitz *et al.*, 2013; Schmidt *et al.*, 2012]. For example, precipitation in many monsoon regions increases in response to elevated GHG concentrations, but these increases are more-than-offset by a full deployment of sunshade geoengineering, resulting in a substantial net reduction in mean precipitation [Tilmes *et al.*, 2013]. It should be noted, however, that there are substantial biases and a large multi-model spread in simulated regional precipitation [Boos and Hurley, 2013]. Curry *et al.* [2014] found that a full deployment of sunshade geoengineering could more than offset the increase in extreme precipitation events expected with global warming [Trenberth, 2011].

Evapotranspiration is also reduced in simulations of sunshade geoengineering deployment compensating the reduction in precipitation to some extent [Tilmes *et al.*, 2013]. Simulations show surface runoff (as measured by precipitation minus evapotranspiration) and soil moisture increase under a full deployment compared with a pre-industrial baseline, though are reduced relative to a high-GHG scenario [Dagon and Schrag, 2016]. Regional differences are reduced relative to scenarios with elevated GHG concentrations alone and runoff and soil moisture is simulated to increase in some regions that show a decline in precipitation (Supplemental Figure 2c) [Kravitz *et al.*, 2013]. Uncertainties in the magnitude of the direct effects of CO₂ on vegetation are the main drivers of the model spread in hydrological changes in tropical land areas between the scenario of full deployment of sunshade geoengineering and the pre-industrial control [Irvine *et al.*, 2014a; Mengis *et al.*, 2015]. Net primary productivity is also projected to increase similarly in both scenarios of elevated GHG concentrations and those with elevated GHG concentrations and sunshade geoengineering combined (Supplemental Figure 2d) [Glienke *et al.*, 2015; Kravitz *et al.*, 2013]. The many factors relevant to terrestrial hydrological change mean that results for any individual variable in isolation, such as precipitation, need to be interpreted with caution, particularly when dealing with global mean values.

Sea-level rise is mainly driven by the thermosteric expansion of the oceans, and the melting of glaciers and the Greenland and Antarctic ice sheets. These contributions all depend strongly on temperature and show a strong path-dependency; for example, ice-mass can be lost much faster than recovered [IPCC, 2013]. Simulations show that

sunshade geoengineering would be effective at reducing temperatures and hence contributions from thermosteric expansion and the melting of land ice, potentially halting further losses if deployed to reduce temperatures below present levels [Applegate and Keller, 2015; Irvine et al., 2009; Irvine et al., 2012; McCusker et al., 2015; Moore et al., 2010]. However, there is considerable inertia and hysteresis in aspects of the ocean and ice sheet responses. The planet may already be committed to the collapse of parts of the West Antarctic ice sheet [Joughin et al., 2014], and simulations suggest this outcome might not be prevented if GHG-related warming were reversed by stratospheric sulphate aerosol injection [McCusker et al., 2015]. Another example of such path dependency is that mass losses from ice sheets happening on centennial timescales cannot be restored on similar timescales [Applegate and Keller, 2015]. Thus, whilst sunshade geoengineering could be effective at reducing additional contributions to future sea-level rise, there could be a substantial amount of future sea-level rise already committed before any potential deployment begins.

The results reported above primarily deal with the effect of sunshade geoengineering on the mean climate response. However, solar geoengineering is also likely to cause changes in weather extremes. Modes of variability, like the El Niño-Southern Oscillation (ENSO), can shift regional climate conditions between different states, giving rise to alternating extremes of weather that may be missed in mean results. The only study of the ENSO response to solar geoengineering did not find any statistically significant changes in either the solar geoengineering or global warming scenarios of the GeoMIP ensemble [Gabriel and Robock, 2015]. Although the experiment's statistical power was weak, and many climate models have poor performance at simulating ENSO, this result suggests any effect may be relatively small as compared to background variability [Gabriel and Robock, 2015].

Like modes of variability, synoptic weather patterns, such as so-called “blocking highs”, high pressure systems which can persist for weeks, can lead to extreme temperature and precipitation events [Lau and Kim, 2012]. If models simulated a change in such weather patterns in response to solar geoengineering it would be evident in the statistical extremes of climate variables, although it should also be noted that certain aspects of observed climate variability are not reproduced by Earth system models [Sillmann et al., 2013a]. As reported above, Curry et al. [2014] found that sunshade geoengineering reduced the overall magnitude of change in most extremes of temperature and precipitation but substantial differences from the pre-industrial climate remained.

Hurricanes and other tropical storms are a key concern for a number of regions but are not well simulated in the CMIP5 models that have been used to assess solar geoengineering to date [Camargo, 2013]. Moore et al. [2015], using a statistical fit of tropical storm activity to surface temperatures, found that stratospheric aerosol injection geoengineering could have the potential to substantially reduce the occurrence of extreme storm surges. These initial results suggest that sunshade geoengineering might offset some of the effects of climate change on daily extremes and interannual climate variability. However, more research is needed.

Supplemental Section 2. Differences between sunshade geoengineering and other types of solar geoengineering

To illustrate how the impacts of solar geoengineering would depend on the type of solar geoengineering deployed and the manner of its deployment, we present here some key differences among some forms of solar geoengineering. All forms of solar geoengineering are anticipated to lower global temperatures. However, the different methods have important differences in the nature and pattern of the forcing effect, which will shape their climate responses. Below, we briefly review the different climate responses to stratospheric aerosol injection (SAI) geoengineering, marine sky brightening, surface albedo modification, and cirrus thinning.

SAI geoengineering which releases sulphate or other aerosols or precursor gases in the tropical lower stratosphere will result in an aerosol cloud with global, though uneven, coverage that scatters light, producing a climate forcing pattern somewhat similar to sunshade geoengineering [*Irvine et al.*, 2016; *Niemeier et al.*, 2013]. However, aerosols also absorb shortwave and longwave radiation, which will warm the stratosphere and upper troposphere, suppressing convection and further reducing the intensity of the global hydrological cycle beyond the effects of sunshade geoengineering [*Ferraro and Griffiths*, 2016; *Niemeier et al.*, 2013]. Whilst a tropical injection of aerosols will produce an aerosol cloud that will likely be more-or-less longitudinally uniform, it will not have a uniform latitudinal distribution and so may not offset regional climate changes as well as sunshade geoengineering [*Kalidindi et al.*, 2014; *Niemeier et al.*, 2013]. In addition, SAI geoengineering will have a number of non-climate side-effects: an increase in diffuse light which may increase vegetation productivity and would reduce concentrating solar power productivity [*Mercado et al.*, 2009; *Murphy*, 2009], a likely reduction in stratospheric ozone which will delay the recovery of the ozone hole [*Tilmes et al.*, 2008], and the deposition of the injected aerosols [*Kravitz et al.*, 2009]. *Irvine et al.* [2016] provide a more in-depth review of the side-effects of this proposal and comparison of the climate effects of sunshade and SAI geoengineering methods.

Marine sky brightening geoengineering could be deployed over any ocean region but is likely to be most effective in unpolluted tropical regions where low-lying stratocumulus clouds form [*Jones and Haywood*, 2012; *Partanen et al.*, 2012]. Simulations suggest that, as marine sky brightening would act primarily over the oceans, it would suppress global-mean precipitation more than sunshade geoengineering [*Bala et al.*, 2010]. However, changes to atmospheric circulation would shift the precipitation onto land in the tropics and extra-tropics, resulting in a smaller reduction in global land-mean precipitation [*Alterskjær et al.*, 2013; *Bala et al.*, 2010; *Niemeier et al.*, 2013]. The patchiness of the climate forcing from marine sky brightening geoengineering would likely cause greater regional changes in climate compared to sunshade geoengineering, but no consistent picture emerges due to differences in the experimental designs employed and the differences in the representation of aerosol and cloud microphysics in the climate models. Marine sky brightening would also lead to increased deposition of salt in some coastal regions, which might pose a risk to agriculture and ecosystems [*Muri et al.*, 2015].

Surface albedo modification of crops, urban areas, and desert areas (for example) cannot produce as large a global cooling effect as other proposed means of solar geoengineering and would be much patchier [Vaughan and Lenton, 2011]. Nevertheless, crop and urban albedo geoengineering may offer a means of reducing regional temperature changes [Ridgwell *et al.*, 2009] and suppressing the occurrence of extreme heat events [Davin *et al.*, 2014]. However, it could also have some small yet significant effects on the position of the inter-tropical convergence zone due to the hemispheric asymmetry of the intervention [Crook *et al.*, 2015; Irvine *et al.*, 2011]. Desert albedo geoengineering has the largest potential global cooling effect, but monsoon precipitation in nearby regions could be reduced by up to 40% [Crook *et al.*, 2015; Irvine *et al.*, 2011].

Cirrus cloud thinning would act primarily to increase outgoing long-wave radiation and is hence not technically a ‘solar’ geoengineering technique, yet it raises similar issues. Cirrus cloud thinning would be most effective when deployed at high latitude wintertime [Cziczo *et al.*, 2013; Storelvmo *et al.*, 2014]. Little work has been done on this proposal to date, but initial studies suggest that at a local level it would produce a radiative effect similar to a reduction in GHG concentrations, and that this might lead to a small intensification of the hydrological cycle as opposed to the suppression expected from solar geoengineering [Kristjánsson *et al.*, 2015].

Supplemental Section 3. Solar geoengineering and the five reasons for concern

The five ‘reasons for concern’ listed below were first elaborated in the IPCC’s third assessment report [McCarthy, 2001], and updated in the following reports, as means to inform the declared intention of the UNFCCC to avoid ‘dangerous climate change’. Here we briefly review the likely effects of solar geoengineering on each of these reasons for concern.

Risks to unique and threatened systems: Climate change threatens ecosystems and societies through the disappearance of, or rapid change of, climate conditions that are conducive to survival. Although solar geoengineering does not address some risks, such as those arising from ocean acidification, studies of coral reef ecosystems indicate that heat stress is the immediate threat and can be mitigated [Couce et al., 2013; Kwiatkowski et al., 2015]. On a regional scale, solar geoengineering could produce novel climate conditions which may give rise to novel risks [Irvine et al., 2010].

Risks associated with extreme weather events: Global warming will give rise to increases in the intensity and duration of high-temperature extremes, increases in heavy precipitation events in several regions, and to more intense droughts in some regions [Seneviratne et al., 2012; Sillmann et al., 2013b]. Solar geoengineering could lead to a general reduction in the intensity of extreme heat events and may also reduce the intensity of precipitation events, though it would reverse reductions in the occurrence of extreme cold events [Curry et al., 2014]. The implications of the reduction in precipitation seen in many regions in simulations of solar geoengineering for hydrological extremes are unclear, as detailed regional hydrological analyses have yet to be conducted.

Risks associated with the distribution of impacts: The impacts of climate change are projected to be the greatest in the Tropics for less-developed nations due to a greater vulnerability of the populations there [IPCC, 2014]. Whilst solar geoengineering may offset many of the climate trends expected with global warming, it may create novel climate conditions, with a different distribution of risks. How solar geoengineering would change disparities in climate hazards is not known, but it would not reduce the disparities in vulnerability that contribute to the overall distribution of impacts.

Global aggregate impacts: This reason for concern relates to measures of the global, aggregate impacts of climate change, e.g. measures of the impacts on global economic activity or of the total number of species lost, etc. Studies to date suggest that solar geoengineering could reduce the magnitude of changes in the climate significantly, however as climate risks depend on changes in the climate in a complex manner simple approaches to assessing its overall risk may not capture the full response [Kravitz et al., 2014].

Risks associated with large-scale singular events: Climate change has the potential to give rise to abrupt and drastic changes in physical, natural or human systems; examples include the potential die-back of the Amazon [Cox et al., 2004], the shut-down of the meridional overturning circulation and the melting of the permafrost at high latitudes [Cheng et al., 2013; Schuur et al., 2013]. Solar geoengineering may be able to prevent or slow the rate of onset of some of these potential large-scale singular events, particularly those which depend primarily on changes in temperature or the build-up of

heat [Irvine et al., 2014b]. However, there are major uncertainties in the responses and thresholds associated with large-scale singular events including to what extent some change could be irreversible (e.g. ice sheet collapse) [Collins et al., 2013].

Supplemental Section 4. Methodology for Supplemental Figure 1

The temperature projections for the Representative Concentration Pathways (RCP) [Meinshausen *et al.*, 2011], RCP 4.5 and RCP 8.5 were reproduced using results from Couce *et al.* [2013], using the University of Victoria intermediate complexity Earth system model (UVic) [Weaver *et al.*, 2001]. The solar geoengineering scenarios shown in Supplemental Figure 1a were produced by simply altering these temperature projections directly.

The precipitation projections shown in Supplemental Figure 1b were produced by using the temperature projections described above with values for the hydrological sensitivity, i.e. percentage change in global-mean precipitation as a function of temperature change, derived from the ensemble-mean response of the Geoengineering Model

Intercomparison Project experiments [Tilmes *et al.*, 2013]. From 4xCO₂-piControl a global-warming value was derived: 6.9% increase in precipitation for a 4.96 K warming = 1.40% K⁻¹ and from G1-4xCO₂ a sunshade geoengineering cooling value was derived: 10.66% decrease in precipitation for a 4.96 K cooling = 2.15% K⁻¹. For the Solar geoengineering scenarios: first, the projected increase in precipitation for the RCP scenario is calculated using the projected temperature described above and then the reduction due to solar geoengineering is subtracted, calculated using the temperature difference between the RCP scenario and the solar geoengineering scenario.

The cumulative CO₂ emissions plotted in Supplemental Figure 1c are derived from the Representative Concentration Pathway (RCP) emissions data found here:

<http://www.iiasa.ac.at/web-apps/tnt/RcpDb>. Cumulative CO₂ emissions are calculated from 1765. It is assumed that solar geoengineering has no effect on CO₂ emissions.

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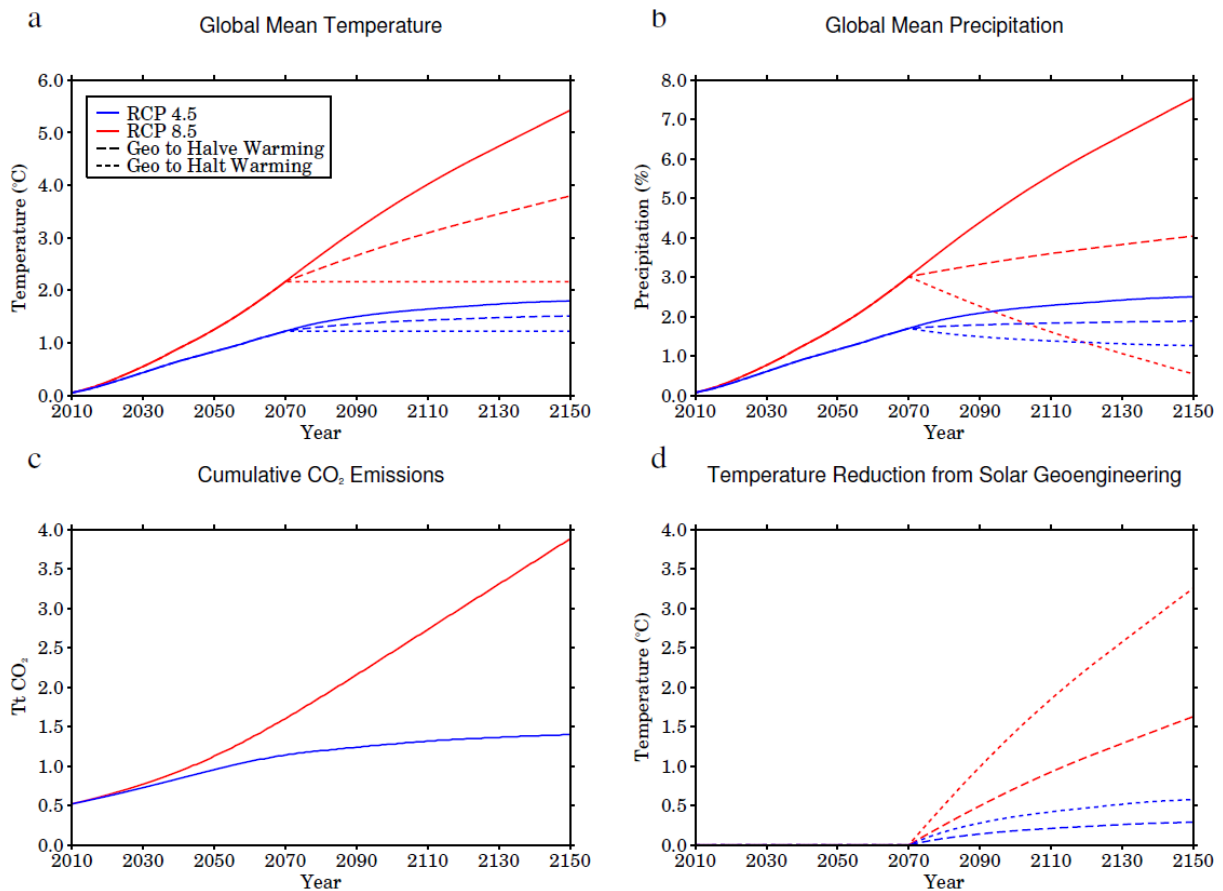
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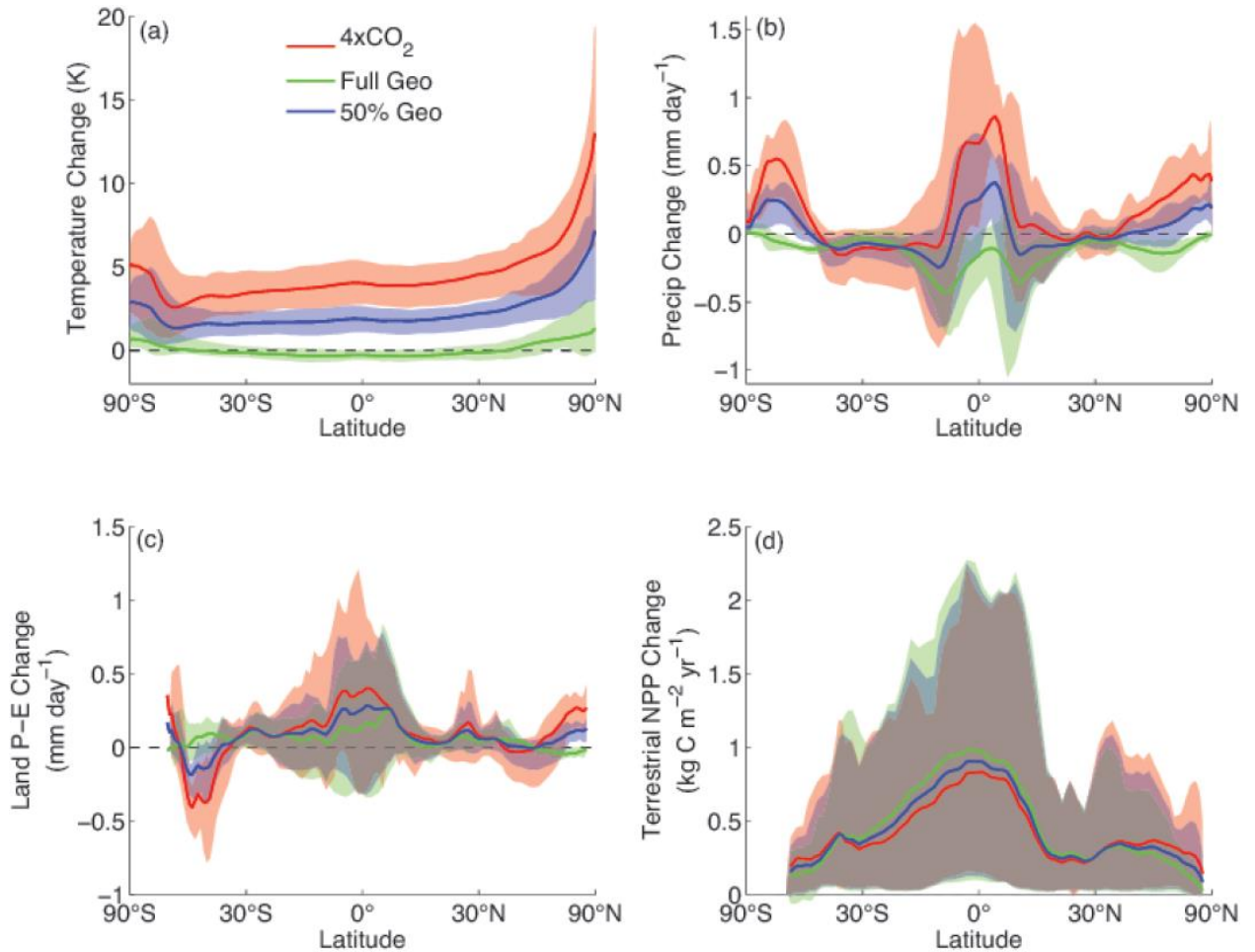
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Supplemental Section 6. Figures



Supplemental Figure 1. Projected changes of (a) global mean temperature, (b) global mean precipitation, (c) cumulative emissions of CO₂ and (d) temperature reduction from solar geoengineering. These variables serve as proxies for potential direct effects of solar geoengineering such as ozone depletion with stratospheric sulphate aerosol injection. Scenarios are plotted for two different emission representative concentration pathways (RCPs) and solar geoengineering scenarios. The emissions scenarios are a high emissions scenario (RCP 8.5, in red) and a moderate emissions scenario (RCP 4.5, in blue). Solar geoengineering scenarios start with deployment in 2070 and are designed to halt further temperature increases beyond 2070 (short-dashed lines, 'Geo to halt warming') and to halve the rate of temperature increase from 2070 onwards (long-dashed lines, 'Geo to halve warming'). Details of how this illustrative figure was produced can be found in Supplemental Section 3.



Supplemental Figure 2. Latitudinal variation in simulated climate response to two scenarios of sunshade geoengineering deployment at elevated CO₂ concentrations. All zonal-mean differences are with respect to a preindustrial control simulation (piControl). Red lines indicate a quadrupling of the CO₂ concentration (4xCO₂), green lines indicate a scenario of full deployment of sunshade geoengineering at 4xCO₂ (Full Geo), and blue lines indicate a scenario interpolated from the first two with 50% of the insolation reduction of the Full Geo scenario (50% Geo). Panels show changes in surface air temperature (a), precipitation (b), precipitation minus evaporation on land (P-E; c), and terrestrial vegetation Net Primary Productivity (NPP; d). The results shown for the solid lines are based on the ensemble mean of the 12 Earth system models used in GeoMIP (Geoengineering Model Intercomparison Project) with coloured shading to show the range of response within the ensemble for each scenario. All values are averaged over years 11-50 of the simulations. The plots shown here are derived from results produced by Kravitz et al. [2013], who provide a more complete description of these experiments, as well as further analysis of these simulations.